

# Primordial Globular Clusters, X-Ray Binaries & Cosmological Reionisation

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## ABSTRACT

Globular clusters are dense stellar systems that have typical ages of  $\sim 13$  billion years, implying that they formed during the early epochs of galaxy formation at redshifts of  $z \gtrsim 6$ . Massive stars in newly formed or primordial globular clusters could have played an important role during the epoch of cosmological reionisation ( $z \gtrsim 6$ ) as sources of energetic, neutral hydrogen ionising UV photons. We investigate whether or not these stars could have been as important in death as sources of energetic X-ray photons as they were during their main sequence lives. Most massive stars are expected to form in binaries, and an appreciable fraction of these (as much as  $\sim 30\%$ ) will evolve into X-ray luminous ( $L_X \sim 10^{38}$  erg/s) high-mass X-ray binaries (HMXBs). These sources would have made a contribution to the X-ray background at  $z \gtrsim 6$ .

Using Monte Carlo models of a globular cluster, we estimate the total X-ray luminosity of a population of HMXBs. We compare and contrast this with the total UV luminosity of the massive stars during their main sequence lives. For reasonable estimates, we find that the bolometric luminosity of the cluster peaks at  $\sim 10^{42}$  erg/s during the first few million years, but declines to  $\sim 10^{41}$  erg/s after  $\sim 5$  million years as the most massive stars evolve off the main sequence. From this time onwards, the total bolometric luminosity is dominated by HMXBs and falls gradually to  $\sim 10^{40}$  erg/s after  $\sim 50$  million years. Assuming a power-law spectral energy distribution for the HMXBs, we calculate the effective number of neutral hydrogen ionisations per HMXB and show that HMXBs can be as important as sources of ionising radiation as massive stars. Finally we discuss the implications of our results for modelling galaxy formation at high redshift and the prospects of using globular clusters as probes of reionisation.

**Key words:** globular clusters: general – galaxies: formation – X-rays: binaries – cosmology:theory

## 1 INTRODUCTION

Hydrogen is the most abundant element in the Universe and it is fundamental to galaxy formation, representing the principal raw material from which stars form. Approximately 16% of the matter content of the Universe at present is baryonic (cf. Spergel et al. 2007), of which about 0.34% is cold gas (most of which is atomic and molecular hydrogen; cf. Table 1 of Fukugita & Peebles 2004). From these numbers we conclude that the bulk of cosmic hydrogen is ionised at present, yet there must have been a period early in the history of the Universe when the bulk of hydrogen was neutral. This is supported by a range of observational data that provides strong and compelling evidence that the Universe underwent an “Epoch of Reionisation” that was complete by  $z \sim 6$ , approximately 1 billion years after the Big Bang

(e.g. Becker et al. 2001; Spergel et al. 2007). During this period the cosmic abundance of neutral hydrogen declined dramatically, “re-ionised” by a background of ionising UV and X-ray radiation whose build-up was very likely linked to the formation of the first generations of stars and galaxies (e.g. Barkana & Loeb 2007).

Understanding the precise nature of the sources of this ionising radiation background remains an important yet largely unsolved problem facing modellers of galaxy formation. It is important because reionisation is expected to have had a dramatic impact on galaxy formation. The presence of a photo-ionising background can inhibit the collapse of baryons onto low-mass dark matter haloes (e.g. Efstathiou 1992; Thoul & Weinberg 1996) and suppress radiative cooling and subsequent star formation within dark matter haloes (e.g. Benson et al. 2002a). Reionisation has been invoked to reconcile the apparent disparity between the observed abundance of satellite galaxies in the Local Group with the

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abundance inferred from simulations of galaxy halo formation within the favoured Cold Dark Matter framework (e.g. Benson et al. 2002b). In addition, there is good reason to believe that reionisation was also important in shaping the faint end of the luminosity function (e.g. Benson & Madau 2003), the clustering of galaxies (e.g. Wyithe & Loeb 2007), the low-mass end of the HI mass function, and perhaps the spatial distribution of globular clusters (e.g. Moore et al. 2006).

However, despite its importance for galaxy formation, reionisation remains a largely unsolved problem because very little is known about the sources of re-ionising radiation. This is because it is technically challenging to observe directly the Universe at  $z \gtrsim 6$ , and will remain so until the advent of next generation instruments such as LOFAR (e.g. Röttgering 2003; Zaroubi & Silk 2005) and JWST (e.g. Windhorst et al. 2006; Haiman 2008). Therefore much of our understanding of the properties of potential sources of reionising radiation comes from a combination of cosmological simulations (e.g. Ricotti & Ostriker 2004; Sokasian et al. 2004) and (semi-)analytical galaxy formation modelling (e.g. Benson et al. 2006; Zaroubi et al. 2007), whose predictions can be tested against limits inferred from the spectral energy density of the radiation background at high redshifts (e.g. Dijkstra et al. 2004) and the electron-scattering optical depth of the cosmic microwave background  $\tau_e$  (e.g. Shull & Venkatesan 2008). Not unexpectedly, UV luminous massive stars (e.g. Wyithe & Loeb 2003; Sokasian et al. 2004; Wise & Abel 2008) and systems in which there is accretion onto X-ray luminous intermediate mass and supermassive black holes (e.g. Ricotti & Ostriker 2004; Ricotti et al. 2005; Zaroubi et al. 2007) have been suggested as likely sources of the ionising radiation background. However, there are many unanswered questions about the nature and origin of these ionising sources, and without direct observations of the galaxy population at  $z \gtrsim 6$  any answers we have will be largely speculative.

There are fossil records of galaxy formation in the high redshift Universe in our own cosmic backyard. Our Galaxy and others in the Local Group have large populations of globular clusters, the bulk of which are metal poor (cf. Figure 2 of Brodie & Strader 2006) and old ( $\sim 13$  billion years old). They appear to be relatively simple systems – their stellar populations appear to be generally coeval, forming in one or more bursts, and many aspects of their dynamical evolution have been studied in detail by direct  $N$ -body methods (see, for example, Hurley et al. 2007, Praagman, Hurley & Power 2008).

This apparent simplicity has led globular clusters to be used increasingly as probes of high redshift galaxy formation (see, for example, the review of Brodie & Strader 2006) because they may, in principle, tell us about the conditions in which galaxy formation proceeded at early times. For example, the inferred ages of old metal poor globular clusters implies that these systems formed at a time when the Universe was undergoing reionisation. Reionisation is expected to quench star formation and therefore globular cluster formation, and so it has been suggested that present-day spatial distribution of metal poor globular clusters around galaxies can be used to measure the redshift of cosmological reionisation (e.g. Moore et al. 2006; Bekki & Yahagi 2006).

However, globular clusters themselves may be sources

of ionising radiation and they could be potentially important for cosmological reionisation. Ricotti (2002) (hereafter R02) has pointed out that massive stars in primordial globular clusters at high redshifts are extremely luminous at UV wavelengths, which means that they could have been effective ionising sources of neutral hydrogen provided the radiation could escape freely from its source (e.g. Ricotti & Shull 2000; Benson et al. 2006). Globular clusters tend to reside on the outskirts of galaxies at the present epoch and if this was the case at early times then the fraction of emitted ionising UV photons that can escape without being scattered or absorbed would have been significant. R02 estimated that massive stars in a primordial globular cluster could emit UV photons sufficiently energetic to ionise atomic hydrogen ( $E_\gamma \geq 13.6$  eV) at a rate of  $\dot{N}_\gamma \sim 3 \times 10^{53} \text{ s}^{-1}$  over the first 4 million years; this is equivalent to a mass of hydrogen of between  $\sim 10^9 M_\odot$  and  $\sim 10^{10} M_\odot$ , depending on the local recombination rate (cf. Dijkstra et al. 2004).

Massive stars in the local Universe tend to form with one or more companions (e.g. Raboud 1996; Mason et al. 1998; Delgado-Donate et al. 2004), and this was likely to be the case in primordial globular clusters. Massive binaries may evolve into high mass X-ray binaries (hereafter HMXBs) once the more massive star collapses to form a compact object, either a neutron star or a black hole. This compact object accretes material from its companion, either via a stellar wind or Roche lobe overflow (RLOF), which results in X-ray emission. The HMXB phase is believed to occur soon after the first compact object is formed and its duration is limited by the main sequence lifetime of the secondary, typically  $\sim 10^7$  years. HMXBs in our Galaxy are observed to emit strongly in X-rays, with typical luminosities of  $L_X \sim 10^{35} - 10^{38} \text{ erg s}^{-1}$  (cf. Liu et al. 2006), and there is good reason to believe that HMXBs in primordial globular clusters at high redshifts would have been as luminous, if not more so (e.g. Dray et al. 2006).

This is very interesting because it suggests that massive stars in globular clusters could have been important as sources of both ionising UV radiation and X-rays during the epoch of cosmological radiation. Certainly, primordial globular clusters would have formed an abundance of UV luminous massive stars that would have had a profound impact on cold star-forming gas in their immediate surroundings. However, could primordial globular clusters have formed sufficient numbers of HMXBs to make an interesting contribution to the ionising X-ray background during the epoch of reionisation? Whereas UV photons are readily absorbed by neutral hydrogen, X-rays are much more penetrating (the photo-ionising absorption cross section of neutral hydrogen decreases with photon energy roughly as  $E_\gamma^{-3}$ ) and can escape into the inter-galactic medium.

In this paper we consider what fraction of massive stars in primordial globular clusters must evolve into HMXBs for these sources to make a significant contribution to the X-ray ionising background. We address this question using a Monte Carlo model of a primordial globular cluster of mass  $10^6 M_\odot$ . We assume that all massive stars form in binaries (see, for example, Dray 2006) and explore what fraction of these binaries must eventually form HMXBs to be an important source of reionising photons.

The layout of the paper is as follows; in § 2.1, we discuss the factors that determine the fraction of massive bina-

ries that survive to evolve into HMXBs ( $f_{\text{sur}}$ ) and, provided they survive, their X-ray luminosities. In § 2.2 and § 2.3, we describe our cluster model in some detail and we compute the effective rate at which neutral hydrogen could be ionised by UV photons from main sequence stars and by X-ray photons from HMXBs. Finally, in section 3 we discuss the implications of our results for modelling of high redshift galaxy formation and the use of globular clusters as probes of cosmological reionisation.

## 2 THE IONISING POWER OF YOUNG GLOBULAR CLUSTERS

In the following subsections, we consider the factors that regulate the formation of high mass X-ray binaries (§ 2.1); we present the details of our globular cluster model and estimate the total X-ray luminosity as a function of time (§ 2.2); and we determine what fraction of this luminosity is available to ionise neutral hydrogen (§ 2.3).

### 2.1 The survival fraction $f_{\text{sur}}$

Not all massive binaries will evolve to become HMXBs. If a massive binary is to survive and become a HMXB, then the stars in the binary must not merge during the more massive stars' main sequence (MS) and post-MS evolution, and the binary must survive the supernova of the more massive star. Whether or not a massive binary merges during the MS lifetime of the more massive star is determined principally by the details of stellar evolution at low metallicities and the initial binary separation. If the binary survives without merging, then the issue of whether or not the binary survives the first supernova depends on a number of factors, including the precise mass of the more massive star, the fraction of mass lost during the supernova and the kick velocity imparted during the supernova. However, binary evolution in globular clusters at very low metallicities is not particularly well understood. Examples of complicating factors include the fact that lower metallicity stars are expected to retain more of their mass because stellar winds are inefficient at low metallicities; therefore these stars will be more massive at the end of their main sequence lives and will form black holes rather than neutron stars (cf. Heger et al. 2003b). This is consistent with the expectation that the ratio of black hole to neutron star remnants is much higher at low metallicities (e.g. Heger & Woosley 2008). Also, less mass is lost during the supernova when the remnant is a black hole rather than a neutron star, and black holes may suffer less violent natal kicks. These arguments suggest that binaries that survive to become HMXBs in primordial globular clusters are more likely to contain black holes, which suggests in turn that they could be more X-ray luminous than typical HMXBs in the local Universe, which are dominated by neutron star systems.

To avoid some of the uncertainty surrounding the stellar physics in primordial globular clusters we introduce a survival fraction  $f_{\text{sur}}$  which indicates the likelihood of an individual binary becoming an HMXB. For each primordial binary, we determine whether or not the binary will remain bound when the more massive star goes supernova by estimating the fraction of mass lost in the supernova explosion;

if the binary remains bound, then it has a probability of  $f_{\text{sur}}$  that it will evolve into a HMXB. We find that typically 70% of high-mass binaries become unbound following the supernova of the more massive star, and so at most  $\sim 30\%$  of the initial binary population will evolve to become HMXBs. We note that those that survive tend to host black holes rather than neutron stars. It is the fraction  $f_{\text{sur}}$  of this remaining  $\sim 30\%$  of bound binaries which go on to become HMXBs. This approach allows us to investigate the potential effectiveness of HMXBs as sources of reionising radiation in a robust manner, even if the factors that determine the value of  $f_{\text{sur}}$  are not well understood, we can speculate on what the most important determinants of  $f_{\text{sur}}$  are likely to be.

### 2.2 Modelling HMXBs in Young Globular Clusters

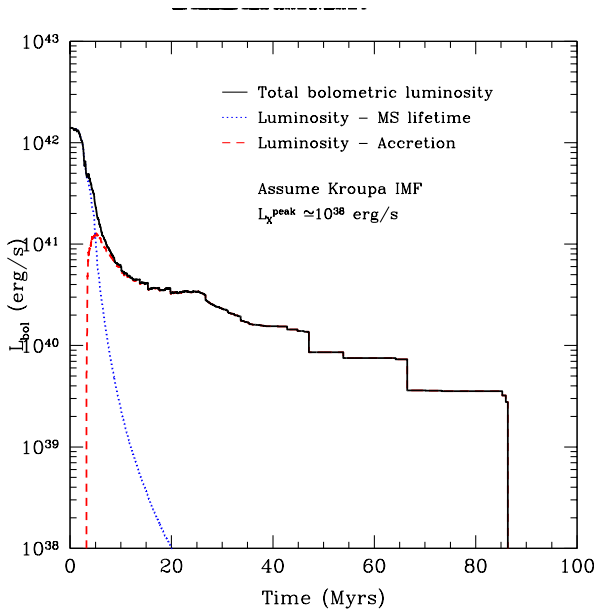
We wish to assess the potential importance of the HMXB population in globular clusters for the X-ray background at high redshifts, and so we require a model of the stellar population in a typical globular cluster. We use a Monte Carlo model of a globular cluster of  $10^6$  stars and follow the evolution of its population of massive stars over its first 100 million years, through their main sequence lives and into the HMXB phase. The main features of our model can be summarised as follows;

- **The Initial Mass Function.** We adopt three different IMFs – those of Salpeter (1955), Kroupa (2001) and Chabrier (2001) – with lower and upper mass cut-offs of  $0.01M_{\odot}$  and  $100M_{\odot}$  respectively. The most important prerequisite for a HMXB to form is that the primary is either a neutron star or a black hole, which sets a lower mass limit of  $M \gtrsim 8M_{\odot}$  for the primary (cf. Figure 1 of Heger et al. 2003a); this is the threshold for neutron star formation. The mean number of stars with masses in excess of  $8M_{\odot}$  and  $20M_{\odot}$  (the threshold for black hole formation) are for Salpeter 2621 (753), for Kroupa 11126 (3174) and for the top-heavy Chabrier 131935 (27024).

- **Binary Formation.** We assume that all massive stars form in binaries. Initial binary orbital parameters are assigned following the approach of Dray (2006) – companion masses are drawn from a uniform distribution between  $0.1$  and  $100M_{\odot}$  and orbital periods are distributed uniformly in logarithm between  $1$  and  $10^4$  days.

- **Massive Star Lifetimes.** Massive stars have short main sequence lifetimes, the duration of which are determined principally by their metallicity. We obtain estimates for these lifetimes using the results of Ekström et al. (2008), Schaerer et al. (1993) and Meynet & Maeder (2000) for  $Z=0$ ,  $0.008$  and  $0.02$  (i.e. solar metallicity) respectively.

- **HMXB Formation.** When the more massive star in the binary reaches the end of its main sequence lifetime, we assume that it goes supernova and forms either a neutron star or black hole. The remnant's mass – which is determined by the mass of the star at the end of its main sequence life – is estimated following Figure 3 of (Heger et al. 2003a). We calculate revised binary parameters (i.e. semi-major axis and period) although there are additional factors which complicate matters (e.g. velocity kick imparted by the supernova). If the system loses more than half its mass in the supernova, it becomes unbound and we remove it from the list of po-



**Figure 1. Variation of Total Bolometric Luminosity with Time.** The light dotted curve corresponds to the contribution of massive stars during their main sequence lives, while the dashed curve corresponds to the contribution of the HMXBs. The solid curve indicates the net luminosity.

tential HMXB candidates; this removes  $\sim 70\%$  of binaries from consideration if we assume a Kroupa IMF. We then draw a fraction  $f_{\text{sur}}$  of the remaining  $\sim 30\%$  at random and consider them as HMXBs.

- **HMXB Luminosities.** If a binary survives and forms an HMXB, we estimate its X-ray luminosity. Although binary parameters are likely to play a role in determining the X-ray luminosity (see, for example, Dray 2006), we take a simpler approach, drawing luminosities from a Weibull distribution with a peak fixed at  $L_X \sim 10^{38}$  erg/s but preventing a HMXB from accreting at greater than its Eddington limit. This sets an upper limit of approximately  $L_X \simeq 1.26 \times 10^{38} (M/M_\odot)$  erg/s. We note that this is consistent with the luminosities of compact X-ray sources in nearby galaxies whose X-ray binary populations are dominated by HMXBs (cf. Figure 1 of Gilfanov et al. 2004); see § 3 for further discussion.

- **HMXB Lifetimes.** We assume that HMXBs are active until the companion star evolves off the main sequence and goes supernova.

Note that although we investigate the sensitivity of our model's results to the choice of IMF (i.e. Salpeter, Kroupa or Chabrier), for clarity we concentrate on models that assume the Kroupa IMF only.

In Figure 1 we show how the total bolometric luminosity of our model cluster varies with time, where we have assumed that  $f_{\text{sur}}=1$ , i.e. all of the  $\sim 30\%$  of the initial massive binary population that remain bound after the primary goes supernova. During the first few million years the luminosity is dominated by the contribution from massive stars, but this declines rapidly as these massive stars evolve off the main sequence and in some cases become HMXBs. The HMXB contribution grows rapidly once the most massive main sequence stars go supernova (after  $\sim 3.4$  million

years for our assumed upper mass cut-off) and dominates the total luminosity from  $\sim 5$  million years onwards.

The total bolometric luminosity for the cluster peaks at  $\sim 10^{42}$  erg/s during the first few million years, but it declines rapidly and has dropped to  $\sim 10^{41}$  erg/s after  $\sim 5$  million years. The luminosity during this period is dominated by the contribution of the massive stars during their MS lives. After  $\sim 5$  million years the decline becomes more gradual, falling by a factor of  $\sim 30$  over the next  $\sim 80$  million years, during which time the luminosity is dominated by the contribution of HMXBs. From this we may conclude that massive stars are indeed energetic sources of radiation during their MS lives and in terms of their total bolometric luminosity they produce as much energy as HMXBs, whose contribution extends over a much longer period.

### 2.3 Implications for Cosmological Reionisation

The total bolometric luminosity is an interesting number, but what fraction of this energy is available to ionise neutral hydrogen? We compute the total number of ionising photons emitted per second by both massive stars during their main sequence lives and by HMXBs and show its variation with time over the first 100 million years of the globular cluster's life in Figure 2. We model the ionising luminosity of massive stars using the Starburst99 code (cf. Leitherer et al. 1999) for the specific case of a cluster of  $10^6$  stars, assuming that all of the stars were formed in an instantaneous burst and Geneva tracks with high mass loss for metallicities of  $Z=0.001$ ,  $0.008$  and  $0.02$  (i.e. solar). The ionising luminosity of HMXBs is calculated by assuming a spectral energy distribution that follows a simple power-law  $F(E) \propto E^{-\alpha}$  between lower and upper energy cut-offs of  $E_{\text{min}}=0.1$  eV and  $E_{\text{max}}=10^6$  eV respectively. The total energy liberated during accretion is then

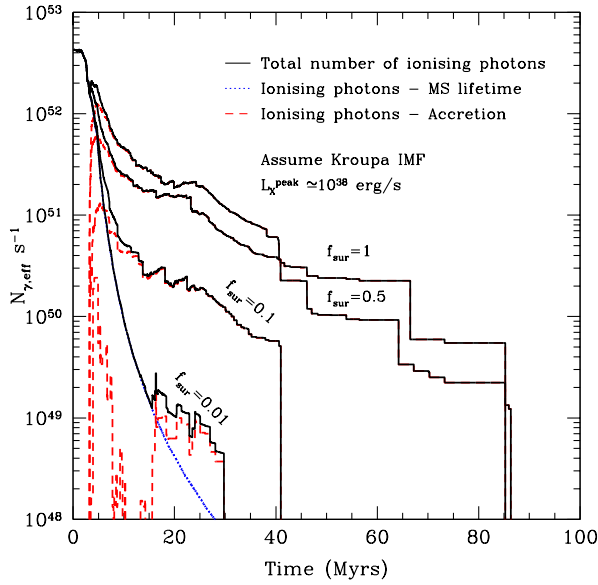
$$E_{\text{tot}} = (A/(2 - \alpha))(E_{\text{max}}^{2-\alpha} - E_{\text{min}}^{2-\alpha})$$

and so given the luminosity it is straightforward to compute the normalisation constant  $A$  for a given HMXB. We estimate the effective number of hydrogen ionising photons to be

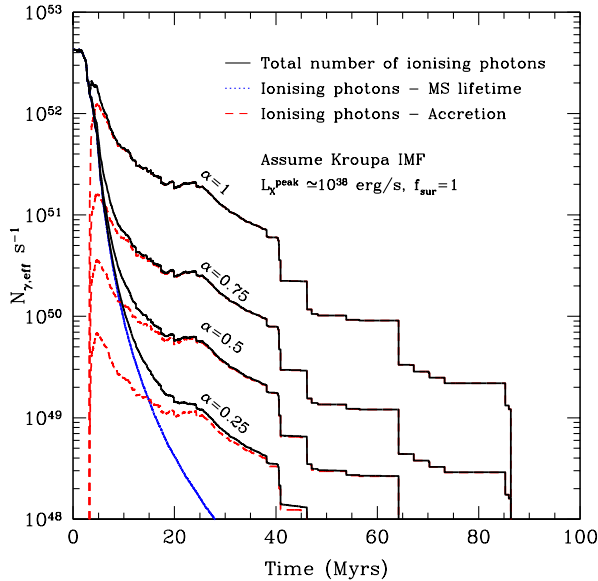
$$N_{\gamma, \text{eff}} = (13.6\text{eV})^{-1} \int_{13.6\text{eV}}^{E_{\text{lim}}} F(E) dE \quad (1)$$

where  $E_{\text{lim}}$  is the energy above which the mean free path of photons becomes of order the Hubble length (i.e. atomic hydrogen becomes transparent to hard X-rays). We obtain  $E_{\text{lim}}$  by requiring that  $\sigma(E_{\text{lim}}) = (H(z)/c)/n(z)$  where  $\sigma(E)$  is the ionisation cross section of neutral hydrogen,  $H(z)$  is the Hubble parameter at redshift  $z$ ,  $n(z)$  is the mean baryon density and  $c$  is the speed of light. For the redshifts in question ( $z \gtrsim 6$ ) we find that  $E_{\text{lim}} \gtrsim 1\text{keV}$ , although the precise value of  $E_{\text{lim}}$  has relatively little impact on  $N_\gamma$ . Equation 1 makes the simple assumption that an energetic photon can ionise multiple hydrogen atoms, and so we treat secondary electrons that ionise hydrogen atoms as effective photons.

In Figure 2 we show how the rate of emission of ionising photons from massive stars (dotted curve), from HMXBs (dashed curve) and from ionising sources regardless of their nature (solid curve) varies with time, assuming  $F(E) \propto E^{-1}$ , which allows us to gauge the effectiveness of HMXBs



**Figure 2. Variation of Rate of Emission of Hydrogen Ionising Photons with Time.**



**Figure 3. Ionising Power and Dependence on Assumed Hardness of Energy Spectrum.**

as ionising sources as a function of  $f_{\text{sur}}$ . At their peak, massive stars produce hydrogen ionising photons at a rate of  $\sim 4 \times 10^{52} \text{ s}^{-1}$  during the first few million years of the globular clusters life, but this declines rapidly. We note that the peak value is a factor of  $\sim 10$  lower than is quoted by Ricotti (2002) but this reflects different assumptions he made about, for example, metallicity ( $Z \sim Z_{\odot}$ ) and the IMF (Salpeter). As one expects, the effective number of ionising photons produced by HMXBs depends strongly on what one assumes for  $f_{\text{sur}}$  and as  $f_{\text{sur}}$  decreases, so too does the strength and duration of the HMXB population as a source of (effective) ionising photons. For survival fractions  $f_{\text{sur}}$  between 50%

and 100% the peak rate at which (effective) ionising photons are emitted is between  $\sim 5 \times 10^{51} \text{ s}^{-1}$  and  $10^{52} \text{ s}^{-1}$ , but this declines gradually and after 30 million years the rate is  $\sim 10^{51} \text{ s}^{-1}$ .

It is important to note that we have assumed a particular hardness for our energy spectrum ( $\alpha = 1$ ); in Figure 3 we show how our results depend on  $\alpha$ , with lower values of  $\alpha$  corresponding to harder energy spectra. As energy spectra become harder (i.e. as  $\alpha$  decreases) HMXBs become less effective as ionising sources; this is unsurprising because the proportion of energetic photons increases as the hardness of the source increases, with a corresponding decrease in the number that can be absorbed by neutral hydrogen. This provides an interesting additional constraint on the precise nature of HMXBs in primordial globular clusters, if they are to be considered as important contributors to cosmological reionisation.

Figure 2 suggests that the hydrogen ionising power of a single young globular cluster is at its most effective when its massive star population is still on the main sequence. However, the ionisation cross section of neutral hydrogen is a strong function of photon energy, decreasing roughly as  $E^{-3}$ , so that the mean free path of a UV photon is much shorter than that of an X-ray photon. Therefore we expect UV photons to be most effective ionising the relatively high density surroundings of galaxies while X-ray photons can escape unscathed from the galaxy to potentially ionise a much larger volume (e.g. Ripamonti et al. 2008). Because UV photons are absorbed in higher density surroundings, we expect recombination to be important and so several UV photons may be required to ionise a single atom of hydrogen. This has been noted by Dijkstra et al. (2004), who estimate that  $\sim 10$  UV photons are required to ionise a single hydrogen atom, compared to  $\lesssim 1$  X-ray photon. This is very interesting because it implies that the HMXB population is likely to be as important as massive stars as a source of hydrogen ionising radiation. Inspection of Figure 2 shows that even if only a few UV photons (rather than the  $\sim 10$  estimated by Dijkstra et al. (2004)) are required to ionise a single hydrogen atom, the relative importance of HMXBs is boosted dramatically and these systems now dominate as sources of ionising radiation. Provided the survival fraction  $f_{\text{sur}} \gtrsim 0.5$  and  $\alpha \simeq 1$ , we would expect a single globular cluster of  $10^6$  stars to ionise of order  $\sim 5 \times 10^7 M_{\odot}$  of neutral hydrogen during its first  $\sim 100$  million years. How precisely one interprets this number is not straightforward because UV photons are absorbed locally whereas X-ray photons contribute to a global X-ray background. Nevertheless, it suggests that the HMXB population that we expect to be present in newly formed globular clusters at high redshifts could have been as important as massive stars for cosmological reionisation (cf. Ricotti 2002).

### 3 CONCLUSIONS

Globular clusters are old, dense and relatively simple stellar systems whose dynamical properties and evolution are well understood. These properties have led to increasing interest in globular clusters as probes of the conditions under which galaxies formed at high redshifts (cf. Brodie & Strader 2006). The study of Ricotti (2002) has suggested that mas-

sive stars in primordial globular clusters could have made an important contribution to cosmological reionisation as extremely luminous sources of UV photons. We have explored the contribution that these massive stars could have made to cosmological reionisation once they evolved off the main sequence, by assuming that a fraction formed in binaries that evolved into HMXBs.

Using a Monte Carlo model of a primordial globular cluster, we have investigated the conditions under which a sufficient number of HMXBs form to have a meaningful impact on the ionising power of the cluster. We assume that all massive stars formed in binaries and we consider only those binaries that remain bound once the more massive star goes supernova, typically  $\sim 30\%$  of massive binaries. Of this  $\sim 30\%$ , we assume that a fraction  $f_{\text{sur}}$  survives to form HMXBs. Note that this is a conservative estimate because we have neglected the effect of mass loss over the MS lifetime of the more massive star.

Our results show that we require  $f_{\text{sur}} \gtrsim 0.5$  if HMXBs are to be as effective as MS massive stars as sources of ionising radiation. Assuming  $f_{\text{sur}} \sim 1$  and a typical X-ray luminosity of  $L_X \sim 10^{38} \text{ erg/s}$ , we find that HMXBs produce ionising photons at an effective rate of  $\gtrsim 10^{51} \text{ s}^{-1}$  over the first 40 million years of the cluster's life. This is comparable to the rate at which massive stars produce ionising UV photons during the first few million years. Note however that result is sensitive to the assumed hardness of the energy spectrum of the HMXBs – the harder the energy spectrum (i.e. the smaller the power-law exponent  $\alpha$ ), the less effective HMXBs are as ionising sources.

By its nature, our modelling is speculative – we know relatively little about the conditions in primordial globular clusters, and little about binary evolution at low metallicities. Yet, we know that many globular clusters formed at high redshifts – at least as many as we can observe in the present day Universe – and we have a good understanding of the initial mass function and metallicities of the stars. This allows us to estimate how many massive stars there might have been and what their typical lifetimes were. Our analysis indicates that under the right conditions, HMXBs in primordial globular clusters can be effective sources of ionising radiation. If these conditions are satisfied (high survival rate  $f_{\text{sur}}$ , softer energy spectra) then it reveals that accretion power onto neutron stars and stellar mass black holes can make a contribution to reionisation.

We have assumed that the typical X-ray luminosity of an HMXB in a primordial globular cluster is  $L_X \sim 10^{38} \text{ erg/s}$ . This is more luminous than is typical of local HMXBs in our Galaxy and the neighbouring Large and Small Magellanic Clouds (e.g. there is a single source with  $L_X \sim 10^{38} \text{ erg/s}$  in the SMC; cf. Shtykovskiy & Gilfanov 2005), but these environments are atypical of the kind we might expect to find primordial globular clusters forming in. Instead, if we consider HMXB populations in galaxies that have undergone recent merging activity and/or show high star formation rates, we find that  $L_X \sim 10^{38} \text{ erg/s}$  is typical (cf. Figure 1 of Gilfanov et al. 2004). For example, the HMXB populations in recent galaxy mergers such as “The Antennae” (cf. Fabbiano et al. 2001) and “The Cartwheel” (cf. Wolter & Trinchieri 2004) have X-ray luminosities in excess of  $L_X \sim 10^{38} \text{ erg/s}$ . This is interesting because, as we discuss below, young star clusters in such galaxy mergers

are likely to be local analogues of primordial globular clusters, and suggests that our assumed X-ray luminosities are reasonable.

It is less straightforward to assess whether or not HMXBs form in the numbers we might expect based on our model in young star clusters in “The Antennae” or “The Cartwheel”. The luminosity functions presented in Gilfanov et al. (2004) and Wolter & Trinchieri (2004) can provide us with some insight, however.

We find that approximately 70% of massive binaries are disrupted before they can become HMXBs in our model. Therefore we expect at most 786 HMXBs for a Salpeter IMF and 952 HMXBs for a Kroupa IMF to survive in a  $1e6$  solar mass cluster, and we introduce a factor  $f_{\text{sur}} \leq 1$  to parameterise the uncertainty as to what fraction of this surviving population evolve into HMXBs. In the most optimistic case,  $f_{\text{sur}} = 1$ . In this case, for our adopted probability distribution, approximately 10% will have luminosities in excess of  $L_X \sim 10^{38} \text{ erg/s}$  – corresponding to between 80 and 100 HMXBs in a single cluster. These numbers will scale in proportion to  $f_{\text{sur}}$ , so  $f_{\text{sur}} = 0.1$  implies between 8 and 10 HMXBs more luminous than  $L_X \sim 10^{38} \text{ erg/s}$ .

Of order 50 HMXB candidates are known in “The Antennae”. Without knowing the detailed spatial distribution of these candidates, it is difficult to do a straightforward comparison – the sources may be associated with a single cluster, in which case  $f_{\text{sur}} = 1$  would seem to be favoured, or they could be associated with 10 clusters in which case  $f_{\text{sur}} = 0.1$  would be favoured. Clearly, this is a very uncertain game to play and would require more detailed modelling (e.g. taking observed distribution of SSCs in the Antennae, populating them with HMXBs and making mock observations), but the numbers do not seem unreasonable.

The crucial factor here is  $f_{\text{sur}}$ . For HMXBs in primordial globular clusters to be an important source of ionising radiation, we require  $f_{\text{sur}}$  to be of order unity. We expect  $f_{\text{sur}}$  to depend on many factors, one of which will be metallicity;  $f_{\text{sur}}$  may decrease as stars become more metal rich, and so it may very well be the case that  $f_{\text{sur}} = 0.1$  rather than  $\sim 1$  in a system such as the Antennae. Establishing how different factors impact upon  $f_{\text{sur}}$  and how these factors may depend on redshift is something that we would like to investigate in future work, but at present the discussion is necessarily speculative.

We have focussed on the ionising power of HMXBs in primordial globular clusters, but it is important to note that the longer mean free path of X-rays compared to UV means that HMXBs in galactic discs could have been as effective as HMXBs in globular clusters. We focus on globular clusters because we have a reasonable understanding of what the IMF could have been, and therefore we have a reasonable idea of how many HMXBs were likely to form. In contrast, we know very little about the initial mass function in star-forming galactic discs at high redshifts, but this is not to say that HMXBs in discs should be discounted. Rather it suggests that stellar mass black holes could make an interesting contribution to reionisation and merit further study. The contribution of globular cluster HMXBs to the reionising background considered in this paper could be considered as a lower limit.

More broadly our analysis strongly indicates that glob-

ular clusters could have been important ionising sources in the high redshift Universe. This has interesting implications for galaxy formation at high redshifts and the use of globular clusters as probes of reionisation. As yet, we do not have a satisfactory theory for the formation of globular clusters within a cosmological context. Nevertheless, if they were to be effective sources of UV radiation then they must have moved quickly from their formation site, presumably a cocoon rich in cold dense gas, to the rarified environs of the hot gaseous halo; if this did not happen on a timescale shorter than a fraction of a few million years, a good fraction of their UV radiation would have been absorbed by the cold dense gas. This would favour globular cluster forming in gas-rich mergers akin to the “super star clusters” that we observe in present day mergers (e.g. Whitmore & Schweizer 1995; Meurer 1995) rather than in the gas-rich discs (e.g. Kravtsov & Gnedin 2005).

We have argued that ionising radiation from the globular clusters could have been effective in ionising neutral hydrogen surrounding their host galaxy, but this radiation could also damage cold dense gas within the galaxy (both neutral and molecular), thus affecting the star formation rate and potentially suppressing further star formation. This has particular implications for the use of globular clusters as probes of cosmological reionisation. The argument is that the spatial distribution of globular clusters around galaxies and in galaxy clusters can be used to measure the epoch of reionisation – the more centrally concentrated the distribution of globular clusters, the earlier the epoch of reionisation. Yet if the star formation efficiency in a galaxy is high, and consequently the rate at which globular clusters form is high, then we might expect feedback from early-forming globular clusters to be extremely damaging for later-forming globular clusters (e.g. Moore et al. 2006). This would suppress the star formation and globular cluster formation efficiency. How could one separate this local effect from the effect of a globally driven period of reionisation? This is a question we shall be pursuing in future work.

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